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DRAWINGS ATTACHED

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(54) RECORDING AND PLAYBACK APPARATUS

(71) We, INTERNATIONAL BUSINESS MACHINES CORPORATION, a Corporation organized and existing under the laws of the State of New York in the United States of America, of Armonk, New York 10504, United States of America (assignees of DONALD WORTZMAN) do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to recording and playback apparatus including improved means for compensating for distortion such as "wow and flutter" in the recording and playback of data, and more particularly to means for correcting the output of magnetic recordings of physiological, seismological or other data-gathering media so that when such output is stored and read, compensation is provided for the shortcomings of the magnetic recording device such as the introduction of "wow and flutter" due in part to speed variations of the recording device.

When a graph recording is being made on an electrocardiograph device for diagnosis of a heart condition, it is at times advisable to make a parallel magnetic tape recording of the electrical pulse beat output. Such a magnetic tape recording not only provides an alternate storage means for the heart condition recording, but also provides a direct and readily available control for a central computer programmed to analyze rapidly and offer diagnosis of the kind of departure from the normal heart beat as indicated by the graph output of the recording. In order to make it possible that such magnetic recordings may be taken in a widespread fashion and may be available in many locations without special expensive recorders it is proposed that cheaper dictation equipment may be used for recording. Cheaper magnetic recording devices are subject to variations in tape speed due to external as well as internal variance of the power source and the result is a recording containing "wow and flutter" distortion of true recordings which are ordinarily of no consequence in vocal recordings. However, should such disturbances be recorded as part of an electrocardiograph chart, they become puzzling to the physician, diagnostician or computer because there is ordinarily no way to sort out erroneous graph portions from the true graph picture of the heart condition. Abnormalities are determined on the basis of waveform, direction, amplitude and time interval of the graph wave pattern.

Heretofore there have been disclosed corrective controls associated with magnetic recording devices for example in the Specification of copending Patent Application No. 33308/66 (Serial No. 1129866) but they are of a rather broad form resting on correction of major diversions from true conditions.

The object of the present invention is to provide for substantially complete compensation so that the most minute erroneous electrical disturbances due to wow, flutter, tape defects, dropouts, or blank periods, for example, are either eliminated or made evident so that a diagnosis may rest on true, accurate and reliable premises.

According to the present invention recording and playback apparatus comprises recording apparatus including means for recording a carrier signal frequency modulated in accordance with a data signal and means for simultaneously recording a tone signal, and playback apparatus including means for deriving a compensating signal from said recorded tone signal representing distortion, and means for subtracting from each portion of the recorded data signal played back the corresponding portion of said compensating sig-

nal modified by a factor dependant upon the instantaneous frequency of said carrier signal.

In order that the invention may be more readily understood, reference will now be made to the accompanying drawings, in which:—

Figure 1 shows a series of ECG chart recordings with and without compensation,

Figure 2 shows a pair of chart recordings, one of which is an ECG recording with spikes (dropouts) and the other of which is a graph illustration which shows a monitor tone also exhibiting the same spikes.

Figure 3 shows a series of ECG normal and abnormal heart condition recordings and associated therewith recordings derived from magnetic tape recordings with and without proportional compensation,

Figure 4 is a block diagram showing a simple FM compensated recording system using a tone control and a single channel,

Figure 5 is a block diagram of a playback or reproducing device for control by the recording of Figure 4 and correction in the reproducing mode,

Figure 6 is a diagrammatic showing of an ECG recording system including a magnetic tape device with proportional compensation devices,

Figure 7 shows a transistorized distortion proportional tone compensation multiplier circuit of the type used in the advanced form of recording and reproducing devices illustrated herein,

Figure 8 is a diagrammatic showing of the playback or reproducing devices controlled by a tape recorder with proportional compensation employed to eliminate distortion completely, and

Figure 9 is a diagrammatic chart showing graphically the signal and tone variations and the frequency modulated controls thereon and also the associated single shot controls for both signal and tone.

Although the invention is illustrated in connection with an electrocardiograph and a magnetic tape control, it is apparent that other forms of input data information may be similarly treated on other forms of recorders, for example optical and electromechanical recorders and reproducers.

Before presenting a brief summary of the description of the novel devices involved, it is believed well to note the usual direct and normal heart form of electrocardiogram as seen at the top of Figures 1 and 3. Since these graph lines are understood to be made directly by an electrocardiograph, it is pertinent to note that such an instrument is designed to record the electromotive force generated by the heart muscle preliminary to the physical contractions of the muscle. Most such ECG devices utilize radioamplification to influence the stylus type of recording which may be viewed instantly. The apparatus is in its essence a voltmeter and the graph recorded is a curve which continually alters with respect to time. In recording the graph the potential difference between two points on the surface of the body is measured. This is accomplished by placing electrodes on the extremities and on the chest.

A normal recording such as that shown at the top of Figure 1 involves a normal sequence of PQRS and T waves. A small low voltage deflection P is caused by the atrial excitation. This is followed by a resting interval PQ which denotes passage of electrical impulses from the atria to the ventricles. A tall rapid deflection signal QRS denotes a ventricle excitation and a ventrical recovery is illustrated by the deflection T: a small slow deflection wave V sometimes follows the T deflection. When the abnormal heart recordings shown in the second and third lines of Figure 3 are compared with some of the data derived from a tape without compensation such as the second line of Figure 1 and the fourth line of Figure 3, it is obvious that a great amount of confusion could be caused if the recordings are not relieved of error before being reproduced for diagnostic control.

The general principles of operation for compensation may be noted by reference to the rather simple forms of recorder and reproducer shown in Figures 4 and 5, respectively. With reference to these Figures, a summary, which is of aid in understanding the more complicated form of controls embodying the invention and found in the later Figures, will now be given. In Figures 4 and 5 an FM modulator is used in conjunction with a magnetic tape dictation recorder 26, and allows the recording of low frequency information below 200 CPS and also eliminates the first order effect of wow and flutter in the recorder. In Figure 4 the incoming signals are shown at the left diagrammatically with the signal 20 representing a heart data signal in the present illustration. Below is a tone signal 21 which may be taken to be 400 CPS. These two signals are supplied respectively to input terminals 22 and 23 connected to an amplifier 24. The incoming low frequency data signal and tone signal are combined and then frequency modulated in the modulator 25 and the resulting signal is fed to the recorder 26 and recorded on the magnetic tape therein. The FM modulator may be taken to have a 2KC centre frequency. The effect of wow and flutter due to speed variation in the recorder 26 is compensated for as described below by recording the tone signal of 400 CPS in addition to the data signal, in a single channel or track on the magnetic tape. It is possible to transmit and receive the data on the tape over telephone lines.

During playback and reproducing as illustrated in Figure 5, the tape signal is fed

to an FM demodulator 27 and the low frequency data and tone (400 CPS) signals are recovered. The data and tone signals, both of which may include distortion components corresponding to "wow and flutter" are separated by filters 28 and 29 and the tone signal is further demodulated by a demodulator 30 so that there appears on the line out of the demodulator 30 only a compensating signal corresponding to the wow and flutter distortion. The low frequency signals representing data and distortion are fed to a difference amplifier 31. If the carrier frequency varies due to wow and flutter, the nominal 400 CPS tone played back will also vary by the same amount and so by demodulating the 400 CPS tone signal and subtracting the resultant compensating signal from the data signal the wow and flutter distortion in the data signal can be eliminated. Therefore the difference amplifier output is low frequency data corresponding to the input data signal 20 shown in Figure 4. The method of recording illustrated has several advantages. There is no chance for intermodulation distortions because there is only one carrier and this enables the recorder to be nonlinear. The data signal together with the tone signal may be transmitted over a regular telephone line and furthermore the loss of the FM carrier will ensure loss of the tone signal so that it is obvious immediately if the signal is lost by the sharp variations in the tone signal frequency.

It will be noted, with reference to the recorder and reproducer shown in Figures 4 and 5, that the recording here is limited to a single track. In the prior art recorders, a separate track is usually required for wow and flutter compensation. In order to do this there is used a frequency modulated zero voltage on the separate compensating track. Frequency modulation is accomplished by assigning to each frequency in a certain range a corresponding voltage such that a change in frequency is proportional to a change in voltage. In the prior art, on playback, since this separate compensating track has no signal on it, any signal that it reproduces is just due to distortion such as wow and flutter. Therefore, by subtracting such a signal from the signal on the separate information track, the distortion due to wow and flutter is cancelled out. This results when the wow and flutter components on each track are the same, or for that part which is the same. The compensating FM signal is referred to as the control tone or the monitor tone.

It is an oversimplification to state that the wow and flutter distortion is cancelled out completely by merely subtracting the demodulated tone signal from the data signal. Since the distortion due to wow and flutter is not only proportional to change in tape speed, but is also proportional to the carrier frequency, when the carrier frequency is at a centre frequency, such as 2 KC, the compensating signal derived from the tone signal might compensate exactly for the distortion. However when the signal carrier is at a higher range, such as 2.8 KC, the distortion would be 40 per cent greater and therefore the compensating signal would be too small to compensate for all the distortion likewise when the carrier signal is at the lower range, such as at 1.2 KC, the tone compensating signal will over compensate, thereby resulting in a distortion of the opposite polarity. Therefore, tone control as described above only compensates fully for distortion at the centre carrier frequency. It is the purpose here to provide compensation for distortion over the full range of frequencies employed for the particular task. In the present illustration it is that of recording physiological data.

Referring to Figures 6 and 8 it is seen that more complicated controls are provided in the apparatus described to take care of distortion occurring at all ranges of frequency modulation and thus provide proportional compensation of a more advanced and accurate form. The need for proportional control is evident when we assume 40 per cent modulation and note distortion of one unit at the centre carrier frequency. The distortion at its +40 per cent carrier frequency would then be 1.4 units and at its −40 per cent carrier frequency, 0.6 units. By using tone compensation as described above the resultant distortion at the centre carrier frequency would be 0 units, 0.4 units at the upper frequency and −0.4 units at the lower frequency. In other words plain tone compensation would improve the average distortion by 5 to 1 and a peak to peak distortion figure by 0. to 0.4 or 3.5 to one. This makes evident that a further improvement would be made as described below if the compensating signal corresponding to the distortion, before being subtracted from the data signal, is first multiplied by the actual signal carrier frequency divided by its centre signal carrier frequency. Then the resultant compensating signal is not only proportional to variations in tape speed, but also proportional to variations in signal carrier frequency. In the previous example of a higher frequency of 2.8 KC as a signal carrier frequency, the compensating signal would be at 2.8 divided by 2.0 times 1 unit, or 1.4 units. This is precisely equal to the distortion in the signal and therefore after subtraction the resultant distortion would be 0 units. At 1.2 KC the result would be similar. In other words this procedure enables one to compensate in a proportional fashion and completely for the distortion at all signal carrier frequencies.

Before describing the complete record and playback circuits of Figures 6 and 8, the

transistorised control circuit illustrated in Figure 7 will be described. This circuit includes an NPN transistor with base 35, collector 36 and emitter 37, two input terminals 32 and 33, a Single Shot 34, a Low Pass Filter 40, and an output terminal 41. The data signal is supplied to terminal 32 and the tone signal is supplied to terminal 33. The output of the Single Shot 34 is a train of pulses, of repition rate equal to the tone signal frequency and of amplitude dependent on the clipping action of the two diodes in the circuit. The clipping level of the diodes is dependent on the operating state of the transistor which in turn is dependent on the value of the data signal at terminal 32.

The tone signal can be distorted from its normal frequency of 400 CPS as described above and the data signal will represent directly the carrier frequency. Therefore the train of pulses supplied to Filter 40 will have an amplitude dependent on the carrier frequency and a frequency dependent on the tone signal frequency. The output of filter 40 will be a compensating signal which will have a value of zero if the tone signal frequency is exactly 400 CPS. If the tone signal is distorted there will be a corresponding output signal from filter 40. This signal will also be dependent on the amplitude of the applied pulse train. The compensating signal output from filter 40 is therefore dependent partly on the distortion of the tone signal and partly on the difference between the actual carrier frequency and the centre carrier frequency of 2 KC.

In a practical example a data signal of +1 volt at terminal 32 represents a carrier frequency 33⅓% off centre frequency and the amplitude of the train of pulses from Single Shot 34 is V. If the tone signal is 400 CPS the output from filter 40 is 0 volts. If the tone signal frequency varies by +1% and the data signal is 0 volts then point A line 38 will be at −1.5 volts and point B line 39 will be at +1.5 volts. As described later in this Specification the output from filter 40 will settle at:—

$$V_{out}=\frac{1}{100}\text{ sec}\times\frac{2\text{KC}\times1.5\text{V}\times0.5\text{ millisec}}{1000\text{ millisec}}\text{ Volts}$$

$$=0.015\text{ Volts}$$

If the carrier frequency increases by 33⅓% to give a data signal of 1 volt, then point A will be at −2 volts and point B will be at +2 volts. The output from filter 40 will settle at:—

$$V_{out}=\frac{1}{100}\text{ sec}\times\frac{2\text{KC}\times2\text{V}\times0.5\text{ millisec}}{1000\text{ millisec}}\text{ Volts}$$

$$=0.020\text{ Volts}$$

Now remembering that if a compensation of one unit is necessary at a signal carrier frequency of the centre at 2 KC, 1.33 units of compensation are necessary at 2.667 KC. Since the compensation was 0.015 volts at 2 KC, and 0.02 volts at 2.667 KC, it follows that by calling 0.015 volts equal to 1 unit, 0.02 volts $=1\text{ unit}\times\frac{0.020}{0.015}=1.33$ units, and exactly what is needed.

Therefore by subtracting the balanced or proportioned output from the signal, perfect compensation is attained, independent of the ranging of the signal carrier, and may be referred to as proportional compensation. This accurate distortion compensating technique is independent of the particular kind of multiplier and also independent of the method for storing the tone which may be on a separate channel or track rather than combined as presented here for purposes of illustration.

In the prior art, distortion compensation is performed without the balancing or portioning or the multiplication steps of the present method. In the case of drawing ECG charts, it is evident that the omission of proper correction results in subtracting too large a correction factor when the ECG is near one edge of the chart and not enough at the other edge, and this deficiency is more noticeable when the ECG has base line drift, or when it is deliberately off centered to accomodate large R or S waves.

Before proceeding more specifically to the solution, it is well to restate the problem as requiring the reproduction of an analog signal previously recorded on a magnetic tape and to do so with good fidelity. The term "good fidelity" implies several characteristics such

as a linearity wherein the change in the reproduced signal is a fixed constant times a change in the recorded signal. Then also there is DC stability wherein for at least one particular recorded voltage, the reproduced voltage is invariant to time of recording and time of reproduction (usually 0 volts in, produces 0 volts out). Then there is also the low noise characteristic wherein the fluctuation in reproduced voltage with no corresponding fluctuation in recorded voltage is held to a minimum. The characteristic of wide band width implies that the range of signal frequency for which the attenuation is small, should be large.

In addition to the requirement of good fidelity, the device is to have good electrical characteristics, be compact, portable and of low cost, and have the ability to have the recorded signal transmitted over telephone lines.

The type of modulation selected for use here, frequency modulation; depends solely on the ability of the recorder to record frequencies faithfully and therefore will compensate for rather gross nonlinearities in the tape system, but this improved linearity is traded for band width. As noted diagrammatically in the first four lines of the graphs on Fig. 9, frequency modulation is accomplished by assigning to each frequency in a certain range a corresponding voltage such that the change in frequency is proportioned to change in voltage. Here, there is assigned to 0 volts the frequency 2 KC and a further assignment of the positive full scale voltage to 2.8 KC and the equal and opposite negative minimum to 1.2 KC and to each frequency inbetween the corresponding linearly interpolated value. The centre frequency was selected as high as the limitations of an inexpensive tape recorder would permit in order that the modulator band width be as high as possible. The percentage of modulation was selected to be large in order to limit the effect of distortion due to fluctuation in tape speed. For example, if the fluctuation of tape speed is assumed to be 1 per cent, then at 2 KC this would correspond to a variation in frequency of 20 CPS. If the percentage of modulation is 40 percent or 800 CPS then the signal to noise ratio would be 800 divided by 20 or 40 to 1. A larger percentage of modulation would increase the signal to noise ratio, however too large a modulation would decrease the lower FM frequency beyond which it could not record the required signal band width, for example 0 to 100 CPS.

The foregoing are not the only reasons for selecting the particular centre frequency and percentage of modulation, but they indicate the most troublesome problem which is distortion due to fluctuation in tape speed often referred to as wow and flutter. Another significant characteristic of wow and flutter is that it is carrier frequency dependent. Assuming the signal is at 0 volts which corresponds to 2 KC (see WN2 represented on the first two lines of Figure 9), a 1 percent fluctuation would correspond to a 20 CPS change in carrier frequency. However, at 2.8 KC (see WN1 in Figure 9) the same 1 percent speed change would correspond to a change of 28 CPS and likewise at 1.2 KC (see WN3 on Figure 9) the change in carrier frequency would be only 12 CPS. Since the change in frequency is proportional to voltage, it follows that in addition to being proportional to tape speed fluctuation, the wow and flutter distortion is also proportional to carrier frequency. The way in which this proportional error is compensated is made more evident hereinafter.

Another method for improving the signal to noise ratio is noted hereinbefore as being accomplished by recording with the data signal a constant tone signal. This is also illustrated diagrammatically in the first four lines of Figure 9. Whenever the FM signal varies due to change in tape speed, the tone also varies by the same percentage change as noted by the disturbances at WN1, WN2, WN3. Since both the carrier and the tone signal are demodulated by the same technique, the compensation signal due to tone signal change will have the same shape as the distortion in the data signal due to change in signal carrier frequency, whenever the latter is due to changes in tape speed. Thus, any distortion due to fluctuation in tape speed will produce similar wave shapes at the outputs of the data signal demodulator and the tone demodulator. As stated hereinbefore, a simplified way of stating the cure would be to say that the demodulated tone signal multiplied by an appropriate constant is subtracted from the demodulated data signal and then the residue is pure data signal less the wow and flutter distortion.

There are two methods for superimposing the tone signal on the data signal. One method is to record the tone signal superimposed on the FM carrier frequency, placing it at a frequency outside the signal carrier bandwidth. A second method is to superimpose modulation. The first method is referred to as "tone on carrier" and the second as "tone on signal". Each of these methods has its own advantages and disadvantages. Which method is better, depends very much on the characteristics of the tape recorder, and the intended usage.

The "tone on signal" method used here does not entail the major disadvantage of the "tone on carrier" method wherein the recorder must be linear in order that the two carriers do not interfere with each other. In an attempt to transmit a signal over phone lines with the "tone on carrier" method, it

would require that the signal be detected and then remodulated without a tone before transmission. In the present "tone on signal" method since there is just one carrier, this restriction does not exist. Having the capability to utilize the same type of circuitry for record and reproduce can be used to advantage to improve the fidelity of the system as noted hereinafter.

A significant consideration to be taken into account when using tone signal compensation is the amplitude of tone signal to be used because it cuts into the usable signal amplitude and therefore tone amplitude should be kept as small as possible. On the other hand, any distortion at the tone signal frequency will tend to distort the tone and consequently produce compensation not present in the data signal thereby adding to the presented distortion. Therefore a compromise has to be sought. Experimentation indicates that when the tone signal utilizes about 20 percent of the useable amplitude, the results come out the best.

A particularly troublesome problem with tape recorders is dropouts such as the one identified by numeral 90 on third line from bottom graph of Fig. 3. In general these graph line breaks are caused by the read-write head not being in contact with the tape magnetic material for a short period of time. This may be caused by obstructions, bouncing of the head due to vibrations or the lack of magnetic material at certain points, etc. Whenever a dropout occurs, the FM signal also disappears. This manifests itself as a signal similar to a sudden drop of FM frequency. Ordinarily it is difficult to detect the distinction of a dropout since it is hard to distinguish between the signal carrier decreasing in frequency and the signal FM carrier disappearing for a short time. The compensating signal can help in making this distinction as noted by the portion of the tone signal identified by numeral 90′ which is coextensive with the break 90 as represented in the lower portion of Figure 3. The tone signal graph line normally varies very little from the centre frequency. However, since the tone signal is superimposed on the data signal, whenever the signal FM carrier disappears at 90, the tone also disappears as at 90′. Then each time the signal varies due to dropouts, the compensating signal will vary more than just its normal few percent and this may also be used to locate a dropout. The changes in dual graph lines generate a marker to make the diagnostician aware, or the computer sense during reproducing that a dropout has occurred.

Attention may be now directed to a description of the FM units with respect to block diagrams shown in the drawings. Figures 6 and 8 are block diagrams of the record and reproduce circuitry, respectively, illustrating the "tone on signal" method of compensation. In these block diagrams Z_1 is the input impedance comprising parallel adjustable resistance and capacitance and Z_2 is the feedback impedance of resistance as noted in the Specification of copending Patent Application No. 33308/66 (Serial No. 1129866).

Blocks 56 and 68 represent resistance summers with 56 used to add the negative of the demodulated tone to the signal which results in subtracting out the distortion due to wow and flutter.

Each of the circuit networks includes a multiplier and shaper such as the multiplier and shapers 61 and 78 and they are similar in type to the transistorized circuit illustrated and described with reference to Fig. 7.

Considering first the upper row of the circuit blocks in Fig. 6, the operation of the recorder may be taken up first and traced as follows. When the input voltage to Z_1, 45, is zero volts, the output voltage of the DC amplifier 47 is such as to maintain the voltage controlled oscilllator 49 oscillating at 2 KC. The oscillating signal from 49, through connection 19, is recorded as an FM signal in recorder 63 and also triggers single shot 53. At each zero crossing of the 2 KC carrier (once every 250 microseconds), the pulse shaper 52 outputs a negative going pulse which fires the 125 microsecond single shot 53. At this frequency, the single shot 53 is negative for as much time as it is positive. The wave shaper 54 clips the positive output of the single shot at $+V_c$ and similarly the negative voltage output at $-V_c$. At an oscillator frequency of 2 KC, the output voltage of the waveshaper is symmetrical. Therefore, the voltage at the output of the low pass filter 55 fed back to Z_2 48 by 41 is zero volts. Neglecting leakage current at the input of the DC amplifier 47, the summing junction, S.J. is also at zero volts, since the voltages applied to Z_1 and Z_2 are both zero volts. The gain of the DC amplifier 47 is so large that when the summing junction varies minutely from zero volts, the output voltage of the DC amplifier 47 and the voltage controlled oscillator 49 vary through their entire range. By virtue of the feedback arrangement, the summing junction automatically assumes a voltage which maintains the voltage controlled oscillator 49 at 2 KC. For any other input voltage, there exists a frequency that produces a corresponding output voltage which maintains the summing junction at the proper level to maintain that frequency. Therefore, the ratio of the feedback voltage to the input voltage will be equal to the negative of the ratio of Z_2 to Z_1 or, in equation form:

$$\frac{V_{t_{\sigma}}}{V_{in}} = -\frac{Z_2}{Z_1} \quad (1)$$

The change in frequency from the frequency at zero input volts (f_o) will be proportional to the input voltage. For example:

$$V_{f_{o'}} = -\frac{V_o}{f_o}(f_{o'}-f_o) \qquad (2)$$

Where V_o is positive and negative clipping level (1.5 volts)

f_o is centre carrier frequency (2KC)

$f_{o'}$ is actual carrier frequency (including "wow and flutter" effects) i.e., $f_{o'}=f_o+Wf_o$

Now, by equations (1) and (2)

$$V_{in}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\,(f_{o'}-f_o) \qquad (3)$$

or

$$V_{in}\sim(f_{o'}-f_o) \qquad (4)$$

Examining the lower row of circuitry in Fig. 6, in addition to the input signal, a 400 CPS tone is also superimposed by oscillator 46 on the input. The 400 CPS tone is demodulated in a manner similar to the signal. However, in this case a positive single shot 34 of 0.625 msec is used (sixth line, Fig. 9). Therefore, the output signal of the multiplier and shaper 61, Fig. 6, is positive and negative for an equal amount of time. Its average output is zero volts and, therefore, does not affect the output of the low pass filter 55 into the summing junction. However, at worst, if the multiplier and shaper output is not symmetrical, its output produces a DC shift.

On reproduce, Fig. 8, the voltage controlled oscillator 49 of Fig. 6 is replaced by the tape recorder 63 in a playback mode. Therefore, provided the speed of the tape recorder does not vary between record and playback, and since the output of the tape recorder 63 is ordinarily passing through the same circuit components as it did during recording, the voltage at the input of Z_2 is the same at it was during recording. Also, since the gain of the DC amplifier is large,

$$\frac{V_{out}}{V_{f_{o'}}}=\frac{Z_1}{-Z_2} \qquad (5)$$

Thus, by combining Equations (1) and (5),

$$V_{out}=V_{in} \qquad (6)$$

In other words, independent of any non-linearities in any of the circuit building blocks, the output voltage is equal to the recorded voltage, provided the characteristics of none of the elements or the supply voltages change between record and playback.

During recording, Fig. 6, the 400 CPS oscillator control of 46 is superimposed on the input signal. During playback, Fig. 8, the recorded waves contain a 400 CPS signal as filtered out by block 73. Therefore, this sensed component is used instead of the 400 CPS oscillator to drive the AC amplifier 74.

It was shown previously (equation 4) that the input voltage during recording was proproportional to $(f_{o'}-f_o)$, or

$$V_{in}=+\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\,(f_{o'}-f_o) \qquad (7)$$

Since V_{out} equals V_{in}, then also

$$V_{out'}=+\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\,(f_{o'}-f_o) \qquad (8)$$

If we consider the output voltage due to the 400^{CPS} tone path, it is similarly also described by

$$\underset{\text{(Tone)}}{V_{t=out}}=-\frac{Z_1}{Z_2}\,\frac{V_{to}}{f_{to}}\,(f_t-f_{to}) \qquad (9)$$

where

V_{to} is the tone clipping voltage similar to V_o

f_{to}=is centre tone frequency (400^{CPS})

f_t=is actual tone frequency

The prefacing sign is negative since the single shot 77 of the tone channel is positive instead of negative as it is in the signal path. During the time when the tone is 400^{CPS}, (f_t-f_{to}) equals zero. Therefore, V_{out} due to the tone is also zero. However, if the tone frequency should change for some reason, $V_{t=out}$ would change proportionally. If equations (8) and (9) are added, then the total output signal, as produced by Res. Summer 68, is represented by

$$V_{out}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\,(f_{o'}-f_o)-\frac{Z_1}{Z_2}\,\frac{V_{to}}{f_{to}}\,(f_t-f_{to}) \qquad (10)$$

Now assume:

$$V_{to}=\frac{f_{o'}}{f_o}\,V_o$$

(Note that the multiplying function of the multiplier and shaper, also shown in Fig. 7, guarantees this)

Then,

$$V_{out}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\left\{(f_{s'}-f_o)-\frac{f_{s'}}{f_{to}}(f_t-f_{to})\right\} \tag{11}$$

Ideally, $f_t=f_{to}$, however a "wow and flutter" speed fluctuation of $W\% \times 100$ then would result in $f_t=f_{to}+Wf_{to}$ and $f_{s'}=f_s+Wf_s$ where f_s is the frequency component due to real signal and

$$W=\frac{W}{100}$$

Substituting in (11)

$$V_{out}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\left\{(f_s+Wf_s-f_o)-\frac{f_{s'}}{f_{to}}(f_{to}+Wf_{to}-f_{to})\right\} \tag{12}$$

Simplifying

$$V_{out}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\left[f_s+Wf_s-f_o-(f_s+Wf_s)\,W\right] \tag{13}$$

$$V_{out}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}(f_s-f_o-W^2 f_s) \tag{14}$$

From Equation (14), it is seen that the "wow and flutter" error is proportional to W^2 and therefore, since W, in even the poorest of tape transports, is only a few hundreths, the error due to "wow and flutter" is less than one thousanth of the full scale signal. It should be noticed that in the circuit schematic shown, V_{to} is derived after compensation and, therefore, is equal to

$$\frac{f_t}{f_o}V_o.$$

Consequently, Equation (11) should read

$$V_{out}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\left\{(f_s-f_o)-\frac{f_s}{f_{to}}(f_t-f_{to})\right\} \tag{15}$$

which would simplify to

$$V_{out}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}(f_s-f_o) \tag{16}$$

The latter equation has no error due to "wow and flutter". This further improvement is only of academic interest, since in either case the theoretical error is much below what is achieved in practice. If tone compensation but not proportional tone compensation was used, V_{to} would be a constant equal to V_o. Then Equation (10) would have resulted in,

$$V_{out}=\frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\left\{(f_s-f_o)+W(f_s-f_o)\right\} \tag{17}$$

From this equation it follows that when $f_s \approx f_o$, the error signal due to "wow and flutter" is approximately zero; however, at all other signal carrier frequencies, the "wow and flutter" component has proportionately larger values. In general, since the percent modulation in most systems rarely gets beyond 40%,

$$\text{Error due to "wow and flutter"} = W(f_s - f_o) \leq 0.4\, Wf_o \tag{18}$$

If no tone compensation was used, then Equation (8) would result in

$$V_{out} = \frac{Z_1}{Z_2}\,\frac{V_o}{f_o}\,\{(f_s - f_o) + Wf_s\} \tag{19}$$

Unlike Equation (17), the error due to "wow and flutter" at $f_s \approx f_o$ is not zero, but is equal to Wf_o. In fact, assuming 40% modulation

$$\text{Error due to "wow and flutter"} = Wf_s \leq 1.4\, Wf_o \tag{20}$$

It should be pointed out that since the output of the amplifier 72, Fig. 8, is used to obtain $V_{t,c}$ when proportional tone compensation is used, V_{tc} is distorted by the de-emphasis network. Therefore, the resultant improvement over nonproportional compensation is not dramatically large. However, if the higher signal frequency components are small, the error introduced has a negligible effect. Hence, if the de-emphasis network is placed after the closed loop, this problem could be alleviated.

Another set of computations may be offered here with reference to the circuit proportions shown near the bottom of Fig. 9.

$$V_{sig} = A\left(\frac{1}{2f_o} - \frac{1}{f_{s'}} + \frac{1}{2f_o}\right) f_{s'} \tag{21}$$

$$V_{sig} = A\left(\frac{1}{f_o} - \frac{1}{f_{s'}}\right) f_{s'} \tag{22}$$

$$V_{t\text{-}ac} = B\left(\frac{1}{f_{to}} - \frac{1}{f_t}\right) f_t = A \cdot \frac{f_{s'}}{f_o}\left(\frac{1}{f_{to}} - \frac{1}{f_t}\right) f_t \tag{23}$$

$$V_t = \frac{f_{s'}}{f_o}\, A\left(\frac{1}{f_{to}} - \frac{1}{f_t}\right) f_t$$

$$V = V_s - V_t \tag{24}$$

$$V = A\, f_{s'}\left(\frac{1}{f_o} - \frac{1}{f_{s'}} - \frac{f_t}{f_o f_{to}} + \frac{1}{f_o}\right) \tag{25}$$

$$V = Af_{s'}\left(\frac{1}{f_o} - \frac{1}{f_{s'}}\right) + A\, f_{s'}\left(\frac{f_{to} - f_t}{f_o f_{to}}\right) \tag{26}$$

Assume the tape recorder changes speed by W%, then:

$f_{s'}$ is made up of two parts

signal $= f_s$

wow and flutter $= Wf_s$

$$f_{s'} = f_s + Wf_s \tag{27}$$

$$f_t \neq f_o \text{ and } f_t = f_{to} + Wf_{to} \tag{28}$$

If there is no wow and flutter $f_t = f_{to}$.

Case I—No Compensation:

by equations (22) and (27)

$$V_s = A\left(\frac{1}{f_o} - \frac{1}{f_s + Wf_s}\right)(f_s + Wf_s) \tag{29}$$

$$V_s = A\left(\frac{f_s + Wf_s}{f_o} - 1\right) \tag{30}$$

signal + W&f

$$V_s = A\left(\left[\frac{f_o - f_o}{f_o}\right] + \left[W\frac{f_s}{f_o}\right]\right) \quad (31)$$

Case II—Proportional Compensation:
by equations (26), (27), and (28)

$$V = A\,(f_o + wf_o)\left[\left(\frac{f_s + Wf_s - f_o}{(f_o + Wf_s)\,f_o}\right) + \frac{-W}{f_o}\right] \quad (32)$$

$$V = A)\left[\frac{f_o + wf_s - f_o}{f_o} + \frac{-(f_s + Wf_s)\,w}{f_o}\right] \quad (33)$$

$$V = A\left[\frac{f_s - f_o}{f_o} - \frac{W^2 f_o}{f_o}\right] \quad (34)$$

Now assuming the wow and flutter is only a few percent, for example, x%:

Then the wow and flutter with compensation eq (34) is only w% of the wow and flutter without compensation eq (31). Consequently proportional compensation improves wow and flutter about two orders of magnitude. Other distortion problems usually prevent the compensation from ever reducing the distortion by more than one order of magnitude.

However, by using the compensation signal to obtain B then

$$B = \frac{f_s}{f_o}\ A \text{ rather than } B = \frac{f_{o'}}{f_o}\ A$$

and then the noises with compensation would be decreased to zero for this application.

Referring again to Fig. 8 it is seen that lines 80 and 81 act as a feedback to bring into the shaper 78 a signal B which is the demodulated f_s and influences the output line 86 of the shaper to produce proportional compensation at the output of the summer 68. Feedback 81, from the DC amplifier 72 to multiplier and shaper 78 is used to obtain the proportional clipping level of the tone channel in order to effect proportional compensation and to provide an ECG reproduce signal to ECG recorder 43 through matching network 82. Feedback 81 of Fig. 8 corresponds to line 32 of Fig. 7. The output of pulse shaper 76, Fig. 8, corresponds to line 33 of the multiplier and shaper of Fig. 7. In Fig. 7, the voltage on line 41~V at 32 times $(f_t - f_{to})$.

The previous compensation techniques only compensated for voltage variation and not time variation. In other words, the resultant wave signal, if viewed on a scope, would look as if it was recorded with a sweep which fluctuated in speed. Fortunately, although the voltage errors due to time variation could be as large as errors due to frequency variation, for most applications the distortions in the former are less noticeable to the viewer. For example, when signals are recorded on strip chart recorders, the variation in paper speed causes time variation distortion, however, this effect is very rarely apparent. One reason why this type of distortion may not be troublesome is that the amount of distortion is proportional to the signal size and, therefore, when viewing small signal fluctuations, the noise is very small; i.e., the signal to noise ratio is a constant, independent of signal size.

A second possible explanation is that the "wow and flutter" is proportional to speed fluctuation, and therefore, the time coordinate is proportional to the integral of speed. Integration tends to smooth out high frequency distortion and consequently decrease the harmful effect.

Low frequency noise is accentuated by integration. In fact, if the DC level of the speed changes between record and reproduce, then, by comparing a long record, this difference becomes quite apparent. In some applications, such as ECG analysis, a few percent change in average speed would throw off some critical measurements, considerably. Therefore, an effort must be made to keep constant the DC components of record and reproduce speeds from machine to machine. If regulating the speed between machines becomes difficult, then the 400 CPS tone could be used for this purpose. If each tape recorder has a well regulated 400 CPS oscillator, as noted here, then any difference between the tape speed during record and playback would be proportional to change in tone frequency. This possibility for introducing automatic control is not performed in the record-reproduce system described here; however, the differences of frequency can easily be detected visually.

A method for compensating for the time fluctuation distortion due to wow and flutter when going Analog to Digital (see line 6, Fig. 3) is to use the tone for determining the sample frequency. For example, if the tone is used as the clock for initiating and closing each sample, then the samples will be equally spaced referred back to the original recording. Assuming that the absence of a tone means that there is no data, then automatically no samples will be taken at those instances. By so doing, the digitized data will not be cluttered with unwanted noise.

While zero crossings of the tone mark off equal time intervals when recording, the amplitude of the demodulated tone channel marks off read time during reproduce.

Previously, it was shown that the reproduce signal is precisely the same as the recorded signal independent of Z_1 and Z_2 provided they remain the same. This is even true if Z_1 and Z_2 have reactive components. By an appropriate choice of Z_1 and Z_2, some additional

"wow and flutter" compensation could be obtained. For example, assume that the signal to be recorded has little power above some cutoff frequency. Then Z_1 and Z_2 could be chosen such that all components of the signal above this cutoff frequency are recorded at a higher amplitude. Since the amount of power above this frequency is small, the over-all percent increase in recording power will be small. Now, on playback, the reversing of Z_1 and Z_2 would have the effect of decreasing frequencies above the cutoff frequency by the same amount as it was increased during recording. Therefore, any noise introduced above this cutoff frequency, not present in the recorded signal, will be decreased during playback, whereas, any signal at these higher frequencies will reproduce distortionless. In those instances where the signal power is concentrated at a very low frequency, this method can decrease the higher frequency components of "wow and flutter" considerably. Also, carrier noise that may not be completely filtered out during reproduce, is also decreased considerably. This type of compensation has been recognized as preemphasis and deemphasis.

In addition to Z_1 and Z_2 being reactive, Z_1 and Z_2 could also be non linear such that small signals produce a proportionally larger change in frequency than large signals. This would improve the signal to noise ratio for small signals. Again, due to the reversing of Z_1 and Z_2, the reproduced output would not be distorted.

Another way to decrease the effect of "wow and flutter" is to utilize as much of the carrier frequency range as possible. This can be done easily, since by just varying the magnitude of the ratio of Z_1 to Z_2, the frequency shift is varied proportionally.

In any system where analog data is being stored on tape, a major problem is its identification. Identification falls into two categories, depending upon its intended use. If the identification is for another person, a very useful form is voice, since it is easily understood by everyone, and also easily coded by everyone. However, since recordings are used most frequently with a computer, it is also important to have a means of identification which is easily decoded by a computer; for example, a digital coding. To do this, the same mechanism used for recording analog information could also be used for coding. The most difficult problem, however, is on the computer end—the decoding. Here it is difficult for the computer to decide which is analog information and which is digital information. One possibility is to make the sequence for digital information so unique that the computer can test for it, and never mistake it for analog information. However, this often increases the length of the program considerably, and puts an unnecessary burden on the digital computer and the programmer. A better method is to record simultaneously some easily decodable information which would identify automatically, for the computer whether the data is analog or digital. In the present case, the 400 CPS tone signal used for "wow and flutter" compensation is ideal for this purpose. Since the tone is 400 CPS whenever there is analog information, it could be made 350 CPS whenever there is digital information. 350 CPS is chosen (line 6, Fig. 3) because it is close enough to 400 CPS so that "wow and flutter" compensation will still be in effect, and also it is far enough away from 400 CPS such that the difference in frequencies can be detected. As pointed out previously, the tone channel was set up so that the single shot duration was such that when the tone is detected, the output signal is zero volts at 2000 cycles. Therefore, at 350 CPS the output voltage would be negative. Consequently, for analog information, the detected tone after filtering would be zero volts, and for digital it would be slightly negative and for any dropouts, it would be random. For short dropouts, (40 ms) this randomness manifests itself as a sharp spike. Thus, the tone plays a very significant role. It is recorded from line 85, Fig. 8, and tells whether the information is digital, analog, or non-existent (note the sixth and seventh lines, Fig. 3).

Any conventional digital coding technique consistent with the bandwidth limitations of the signal channel could be used. However, since the amount of digital coding for many analog base problems is limited to just a few characters, it is more important that the method used be simple and convenient rather than conserve bandwidth. Therefore, a useful method is to use different voltage levels to detect the different characters. However, if more than 10 characters are necessary, separation of the characters may be difficult and consequently, it may be advisable to use sets of two or more consecutive voltage levels to detect different characters.

Using different voltage levels to detect different characters has several advantages:

1. It is simple to generate.

2. It can be detected with an ADC normally used to encode the analog output of the tape recorder.

3. It can be visually encoded from a strip chart recording.

4. It can be heard, if played into a speaker, and with practice understood.

The bottom two lines of Figure 3 show test recordings made while demodulating high, low and centre frequency recordings with either conventional compensation or improved proportional compensation. It is evident that the ragged line of the ordinary compensation made reveals that noise continues to influence the recording in a bad wav. On the other hand, the smoothness of the final line with proportional compensation applied, shows that

substantially all the noise influences are eliminated.

WHAT WE CLAIM IS:—

1. Recording and playback apparatus comprising recording apparatus including means for recording a carrier signal frequency modulated in accordance with a data signal and means for simultaneously recording a tone signal, and playback apparatus including means for deriving a compensating signal from said recorded tone signal representing distortion, and means for subtracting from each portion of the recorded data signal played back the corresponding portion of said compensating signal modified by a factor dependant upon the instantaneous frequency of said carrier signal.

2. Apparatus as claimed in claim 1 in which each portion of the said compensating signal is modified by multiplying it by the ratio of the instantaneous carrier frequency to the centre carrier frequency.

3. Apparatus as claimed in either of the preceding claims comprising means for combining said data signal and said tone signal and modulating said carrier signal in accordance with said combination.

4. Apparatus as claimed in any one of the preceding claims in which said signals are recorded on a recording device designed for recording dictation.

5. Recording and playback apparatus substantially as described with reference to Figures 1, 2, 3, 6, 7, 8 and 9 of the accompanying drawings.

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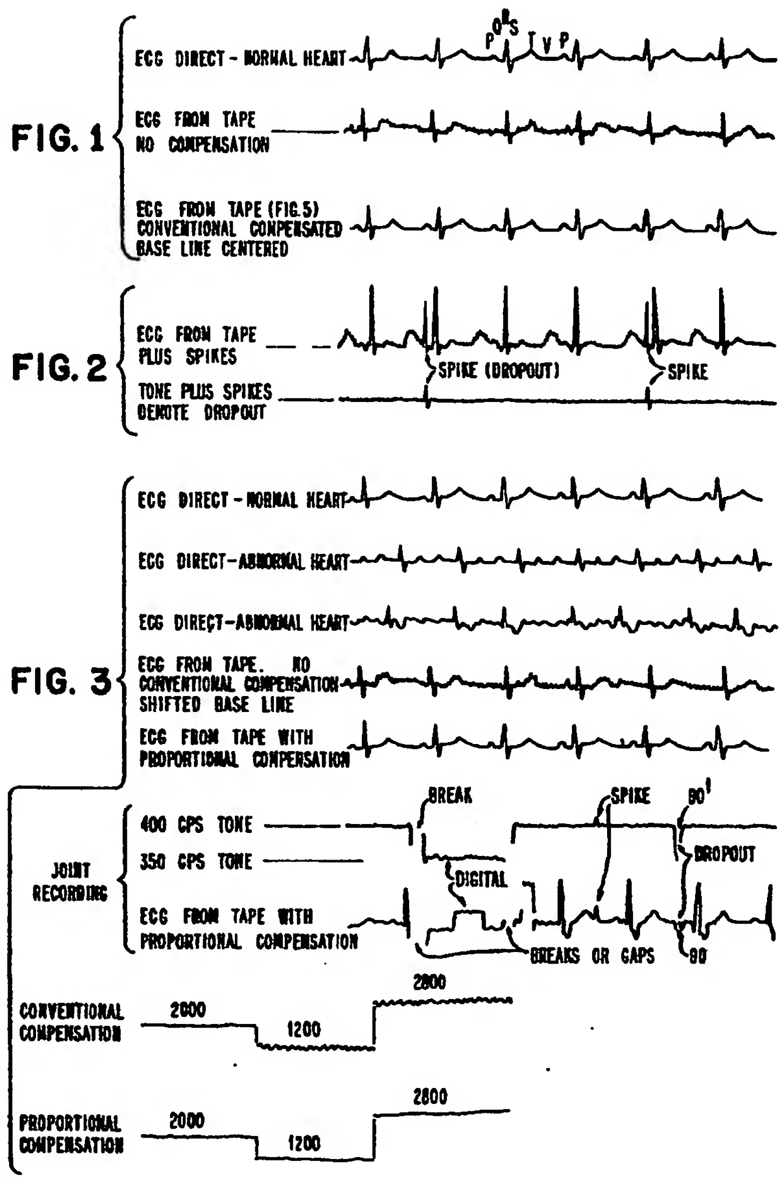


FIG. 1
ECG DIRECT - NORMAL HEART
P Q R S T V P
ECG FROM TAPE NO COMPENSATION
ECG FROM TAPE (FIG.5) CONVENTIONAL COMPENSATED BASE LINE CENTERED
FIG. 2
ECG FROM TAPE PLUS SPIKES
SPIKE (DROPOUT)
SPIKE
TONE PLUS SPIKES DENOTE DROPOUT
FIG. 3
ECG DIRECT - NORMAL HEART
ECG DIRECT-ABNORMAL HEART
ECG DIRECT-ABNORMAL HEART
ECG FROM TAPE. NO CONVENTIONAL COMPENSATION SHIFTED BASE LINE
ECG FROM TAPE WITH PROPORTIONAL COMPENSATION
JOINT RECORDING
400 CPS TONE
350 CPS TONE
ECG FROM TAPE WITH PROPORTIONAL COMPENSATION
BREAK
SPIKE
80'
DROPOUT
DIGITAL
BREAKS OR GAPS
80
CONVENTIONAL COMPENSATION
2000
1200
2800
PROPORTIONAL COMPENSATION
2000
1200
2800

FIG. 4

RECORD

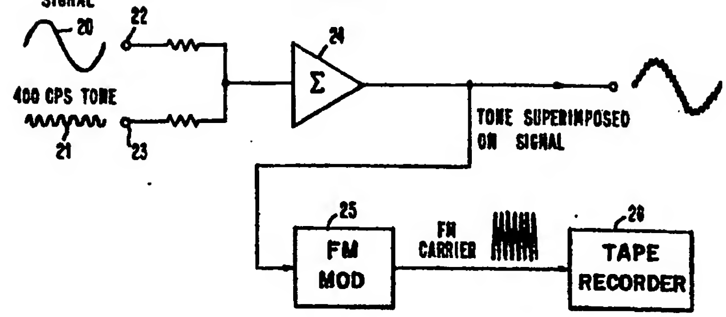


FIG. 5

REPRODUCE

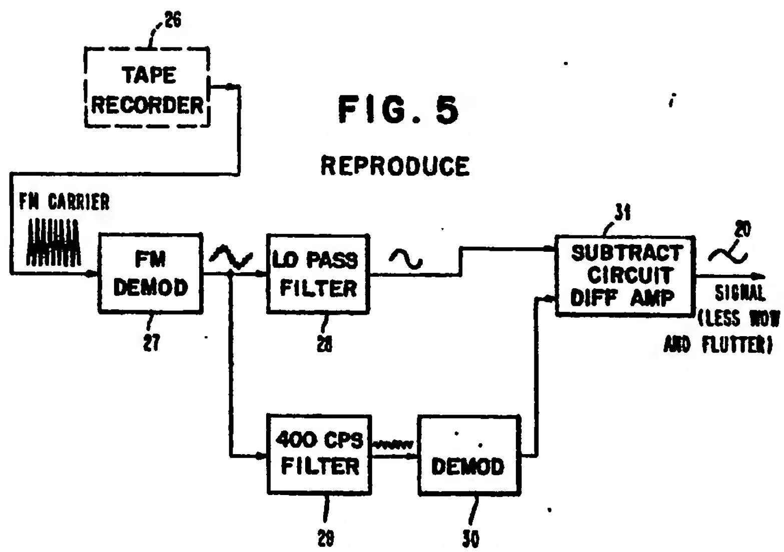


FIG. 6

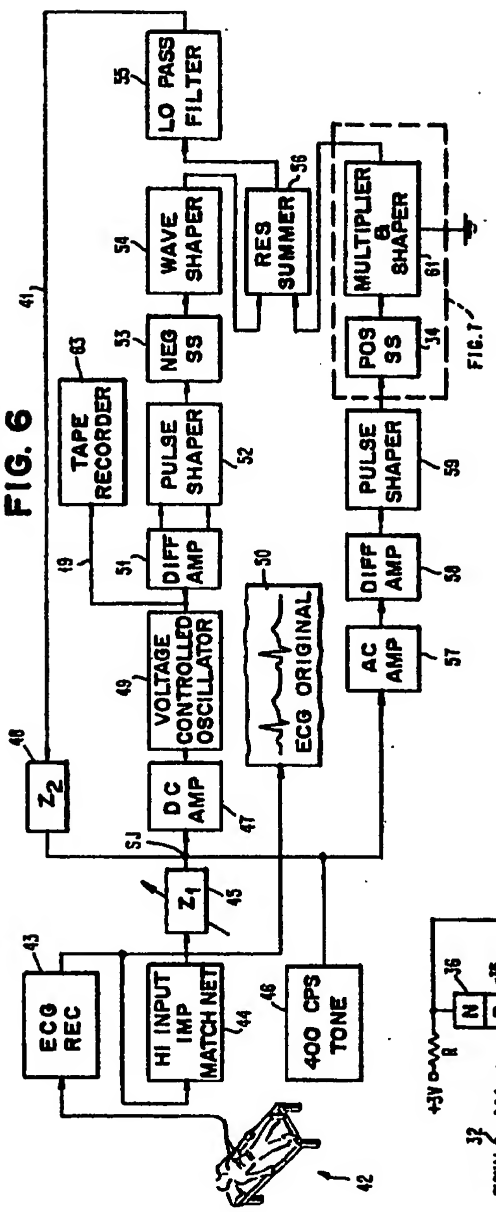
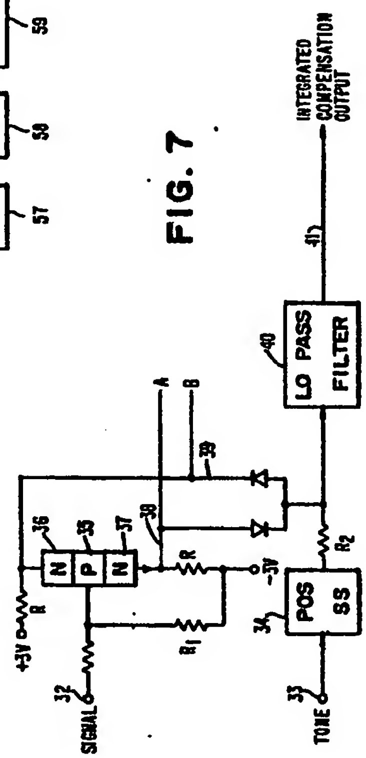

LO PASS FILTER
WAVE SHAPER
RES SUMMER
MULTIPLIER & SHAPER
NEG SS
POS SS
FIG. 7
TAPE RECORDER
PULSE SHAPER
DIFF AMP
VOLTAGE CONTROLLED OSCILLATOR
ECG ORIGINAL
AC AMP
Z_2
DC AMP
SJ
Z_1
ECG REC
HI INPUT IMP MATCH NET
400 CPS TONE

FIG. 7


INTEGRATED COMPENSATION OUTPUT
LO PASS FILTER
A
B
N
P
N
R
+3V
-3V
R_1
R_2
SIGNAL
POS SS
TONE

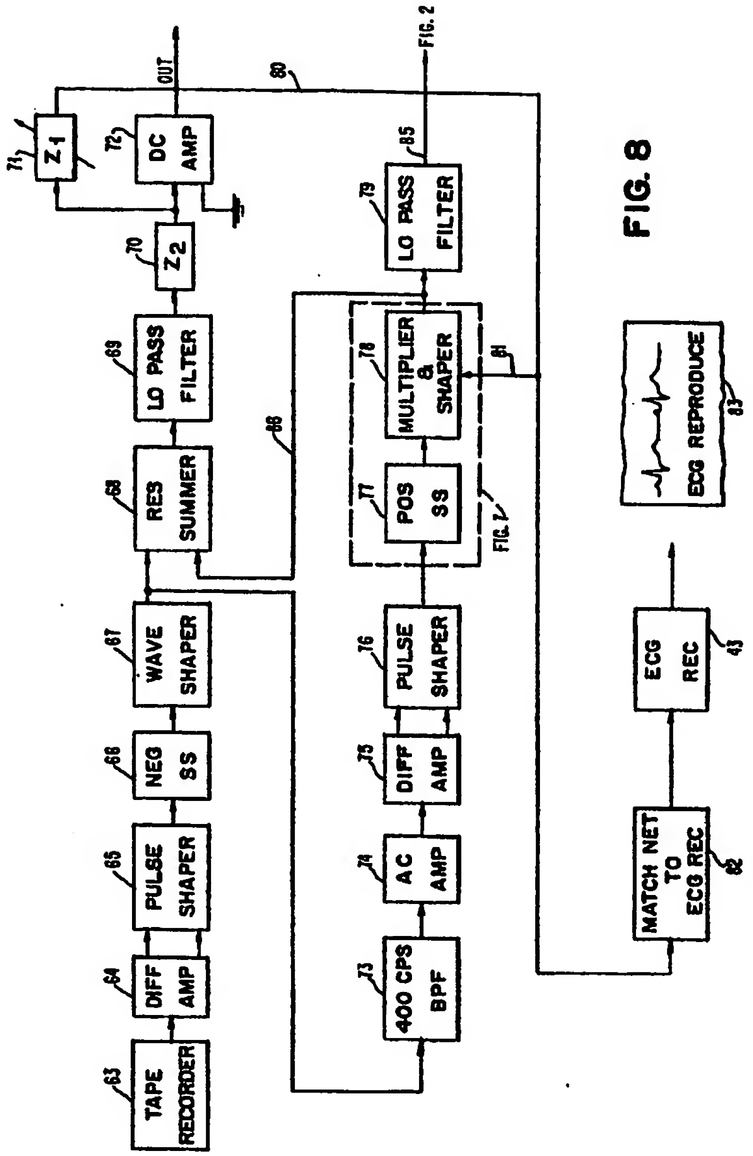
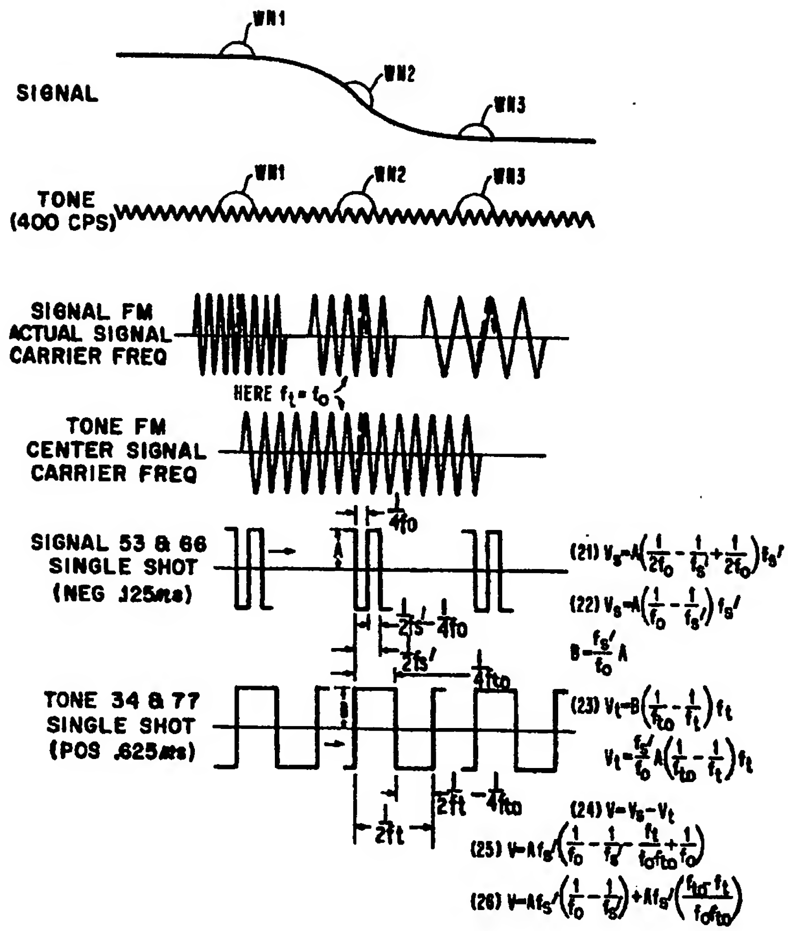

TAPE RECORDER
DIFF AMP
PULSE SHAPER
NEG SS
WAVE SHAPER
RES SUMMER
LO PASS FILTER
Z2
DC AMP
Z1
OUT
FIG. 2
400 CPS BPF
AC AMP
DIFF AMP
PULSE SHAPER
POS SS
MULTIPLIER & SHAPER
LO PASS FILTER
MATCH NET TO ECG REC
ECG REC
ECG REPRODUCE

FIG. 8

FIG. 9



(27) f_s' IS OF TWO PARTS, SIGNAL—f_s, WOW & FLUTTER—Wf_s,
$\Rightarrow f_s' = f_s + Wf_s$

(28) $f_t \neq f_{to}$ AND $f_t = f_{to} + Wf_{to}$
IF THERE IS NO WOW AND FLUTTER $f_t = f_{to}$